The Relation of Reaction Time to Measures of Intelligence, Memory, and Learning

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THE RELATION OF REACTION TIME TO MEASURES OF INTELLIGENCE, MEMORY, AND LEARNING

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The Relation of Reaction Time to Measures of Intelligence, Memory, and Learning*

I. INTRODUCTORY

In the early days of any science, the principal object of research is to build up as large a body of fundamental data as possible; consequently every phenomenon which is discovered is considered of sufficient interest to be studied. After this preliminary work, however, it is desirable to determine which phenomena are the most important, and will most repay further study. Clearly, a phenomenon which does not bear any relationship to other phenomena judged to be significant, should not itself be considered of very great value. The test of importance, therefore, should be the number of other significant phenomena to which the given phenomenon is related, and the degree of such relationships.

Few phenomena in psychology have been studied more than reaction time. In almost all the studies in this field, however, the speed of response has been studied for its own sake, its importance being taken for granted, and there has been little thought of determining its relationship to the principal psychological capacities. Investigators sought first to determine the average time of the reaction as a whole and also the separate times of the various mental processes which they believed entered into the reaction, with the idea of establishing a series of "psychological constants." Much of the work of Donders and Wundt, for example, was along these lines. The great variability of the results, however, indicated that the supposed "constants" probably had no existence in fact, but it did direct attention to individual differences in reaction time, which in turn became an object of investigation.

The phase to which the greatest amount of attention has been directed, however, is the influence of various conditions or factors, both external and internal, on reaction time. There are, for example, studies of the influence of the sense organ stimulated; the part of the sense organ stimulated; the magnitude, intensity, and duration of the stimulus; the length of the fore or warning period; the direction of attention; distraction; incentives; combinations of stimuli; practice and fatigue; drugs; type of reacting movement; etc. The results of studies of this nature have been summarized frequently, and an additional summary would be of no value in connection with the present investigation. Reference (5)† contains a good summary of the earlier studies, particularly those of Cattell, who investigated many phases of reaction time. Another summary is given by Woodworth and Poffenberger (24). More recent studies (i.e., up to about 1923) are discussed in an article by H. M. Johnson (10).

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* This study is one of a series of researches (under the general direction of Professor H. E. Garrett) supported by a grant from the Council for Research in the Social Sciences, Columbia University.

In another type of study, reaction time is not studied for its own sake, but serves as a tool in the investigation of some other phenomenon. A very early example is the work of Helmholtz, who attempted to determine the speed of nerve conduction by means of reaction time. Later, Henmon (6) used discriminative reaction time (which he called the time of perception) as a measure of differences in sensations. Poffenberger (13) employed reaction time as a means of arriving indirectly at the time of conduction through a synapse, by comparing the times for reactions involving direct and indirect nerve conduction paths. Woodrow (23) used the effect of irregular preparatory or warning intervals upon reaction time as an indicator or measure of the degree of attention.

A more recent type of study has the practical object of predicting the amount of some capacity or trait possessed by an individual. A number of tests, often including reaction time, are correlated with a measure of the capacity in question, in the hope that some of the correlations will prove large enough to aid in prediction. In this category belong the attempts made during the war to devise tests for selecting aviators, of which the study by G. M. Stratton and others (17) is typical. Men at aviation fields were rated by officers for flying ability, and were also given a number of tests, one of which was discrimination reaction time. The reaction was not the simple movement of the usual laboratory experiment, however, but a series of motions of hands and feet imitating the movements made in operating an aeroplane. The time was measured to

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† The figures in parentheses refer to the list of references at the end.

.1 second. The initial correlation between reaction time and rated aviation ability was .16, which was raised to .25 when the effect of errors was eliminated by partial correlation.

In a study of the "practical" type, it occasionally happens that an investigator will report, incidentally and without much discussion, a correlation between reaction time and intelligence or some other psychological capacity. For example, Moss (11) made use of reaction time in developing tests for automobile drivers. Happening to have available the Army Alpha Test scores for some of his subjects, he investigated the relation between the test scores and reaction time, and states briefly that there is a correlation, those having higher intelligence scores tending to react faster. He does not give the numerical value of the correlation.

Finally, there is a type of study in which reaction time is correlated with psychological abilities or capacities of the "higher" type, such as memory, learning, and intelligence, with the object of disclosing relationships which might be of importance in psychological theory. Very little work has been done in this field.

In 1894, J. A. Gilbert (4) made a number of mental and physical measurements upon a thousand school children. Among these measurements were tests of simple and "discrimination and choice" reaction time. Reactions were made to a disk on the end of a rod, the time being measured with a Ewald chronoscope. The median of ten trials was taken as the representative value. The correlation method was not used, but averages are reported for three groups: bright, average, and dull, as determined by teachers' estimates. No statement is made of the statistical reliability of the reaction time measurements or of the intelligence ratings. The results are:

	Reaction time in thousandths of a second	
	Simple reaction	Discrimination and choice
Bright	207	401
Average	213	402
Dull	224	420

These figures indicate, at least, a slight positive correlation between speed of reaction and intelligence.

W. C. Bagley (1) obtained the reaction times of school children by means of Jastrow's card sorting apparatus, but does not describe his procedure. He compared reaction time with class standing by the "averages of groups" method, and found no relation.

C. Wissler (21), reporting studies made on Columbia College students by Cattell and himself, gives correlations of reaction time with a number of other measurements, among which were: logical memory for a paragraph; pitch memory; class standing; marking out A's; naming colors; association time; and movement time. The reactions were simple reactions to sound measured with a Hipp chronoscope, the average of three or five trials being taken. No statement of the statistical reliability of the reaction time and other measures is made; in fact, failure to consider this factor is perhaps the chief fault of this pioneer piece of work. The correlations of interest in connection with the present problem are:

reaction time with logical memory: +.12 (96 cases)
reaction time with class standing: —.02 (227 cases)

According to Sommerville (16), Cattell and Wissler " . . . were the first to apply the processes of mathematical correlation to the problem of psycho-physical relationships."

Peak and Boring (12) report a study entitled: "The Factor of Speed in Intelligence," in which reaction time was one of the measures of speed employed. The reactions were of the visual type, being made to the appearance of a black dot in a hole in a screen, and the times were measured with a Sanford chronoscope. Each subject made 100 reactions. The reliability of the reaction time measurements is not given, but was probably satisfactory. The reaction times were correlated with total scores on the Army Alpha and Otis intelligence tests, the value obtained being +.90 for each test. This figure is so high that, if confirmed, it would indicate an extremely important relationship. The correlations were computed from data on five subjects.

Of the two correlation studies just reported, one gives a very low correlation of reaction time with "higher" abilities; the other gives a very high correlation. In one, a sufficiently large number of subjects was used, but not enough reaction times were obtained from each subject to insure a reliable measure; in the other, enough reaction times were measured, but the number of subjects was too small to warrant the placing of much confidence in the reliability of the correlation.

In none of the studies reported was any attempt made to determine the statistical reliability of the reaction time test, an essential factor where relationships are to be investigated.

Evidently, the question of the relation between reaction time and the higher abilities is not yet settled. Regarding the importance of the problem, Peak and Boring say (12, p. 93) : "It is needless to point out that, if the relation of intelligence (as the tests have tested it) to reaction time of any sort can finally be established, great consequences, both practical and scientific, would follow. Practically we should have a precise and economical way of testing a fundamental and socially important individual difference."

II. THE PROBLEM AND METHOD

The present study seeks to determine the correlation between speed of reaction and certain measures of intelligence, memory, and learning. The investigation was limited to response to visual stimulation, but both simple and discriminative reactions were used. In the latter case reactions were made to stimuli arranged so as to give five degrees of difficulty of discrimination.

The study was made upon a group of about 100 Columbia College undergraduates. The reaction time tests were given individually, but the tests designed to measure intelligence, memory, and learning were for the most part administered to groups.* A series of product-moment correlation coefficients was then obtained, each type of reaction time being correlated with each of the other tests. Partial correlation also was employed in order to effect a more complete analysis of the data.

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* The reaction times were measured by the writer, but the scores on the other tests were obtained from the files of Professor H. E. Garrett, under whose direction the memory and learning tests had previously been administered.

III. THE REACTION TIME APPARATUS

The stimulus for reaction was in every case the lighting of one or more 2.5 volt mazda flashlight lamps. Thirty-two of these lamps were mounted upon a board, 27 x 37 cm., placed before the subject at a distance of 125 cm. A vertical black strip 4 cm. wide divided the board into two equal parts. A group of sixteen lamps was mounted upon each half, each group being arranged in four rows, four lamps to a row, with a spacing of 4 cm. in both horizontal and vertical directions. Only five lamps in each half were actually used, the others being merely for the purpose of producing a uniform appearance. Each of the ten "active" lamps was electrically connected through a wire in a cable to one of a number of brass wire fingers or springs which were mounted in a row on a hinged carrier above a brass contact plate. Between the springs and the plate passed a strip of perforated paper somewhat similar to the music roll of a player piano. The perforations were in rows about 2 cm. apart, each row being used to control the arrangement of one combination of stimulus lamps. The spring carrier was raised by the experimenter and the paper adjusted until the first row of perforations was under the springs; then the carrier was lowered, and those of the springs which were over perforations made contact with the brass plate underneath, while the remaining springs rested upon the paper. The springs which made contact with the plate connected their corresponding lamps with the experimenter's stimulus key. The depression of this key lighted the lamps which were connected with it, thus presenting the first stimulus to the subject. After each reaction the experimenter moved the succeeding row of perforations under the springs; thus the different combinations of stimulus lamps were presented in a fixed order, which was the same for all subjects.

The reaction times were measured with a Hipp chronoscope, using the Dunlap circuti without springs as described by Poffenberger and Morgan (14).

The depression of the experimenter's stimulus key, which lighted the stimulus lamps, also started the chronoscope. Theoretically, the lamp filaments did not reach full incandescence instantaneously when the current was applied. The lag was not noticeable, however, and since it was constant it did not affect the correlations. The subject reacted by lifting his finger from one of the two telegraph keys mounted before him, thus stopping the chronoscope. The keys were fitted with extra contacts which caused a small lamp at the chronoscope to light whenever the subject made a false reaction, that is, raised the wrong key or both keys. The stimulus lamps remained lighted until the experimenter raised his key, which he did as soon as the subject had reacted.

The chronoscope was calibrated by means of a freely falling steel ball, being adjusted until the average of ten readings did not differ from the computed time of the ball's fall by more than 0.5 milliseconds.* The mean variation of ten calibration readings from their average was usually about 0.75 ms. The chronoscope was checked at least once a day, but did not often need adjustment.

The experiment was performed in a room illuminated by artificial light, the source of light being a 150-watt mazda lamp which was screened so that the subject's end of the room received only light reflected from the walls and ceiling. This resulted in a diffused, practically uniform illumination of moderate intensity. The subject was seated at one end of a table, with the two reaction keys conveniently placed in front of him. The board with the stimulus lamps was placed at the other end of the table. All the rest of the apparatus was placed on the experimenter's table, which was screened off from the subject.

A wiring diagram of the apparatus is given in Diagram I.

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* "Milliseconds" (abbreviated "ms") is the term recommended by the U. S. Bureau of Standards to replace the term "sigma" as a designation for the time unit of one thousandth of a second. "Sigma" is not descriptive, and is, moreover, frequently used to designate the standard deviation.

IV. THE REACTION TIME MEASUREMENTS

The various combinations of lights which served as stimuli are shown in Diagram II.

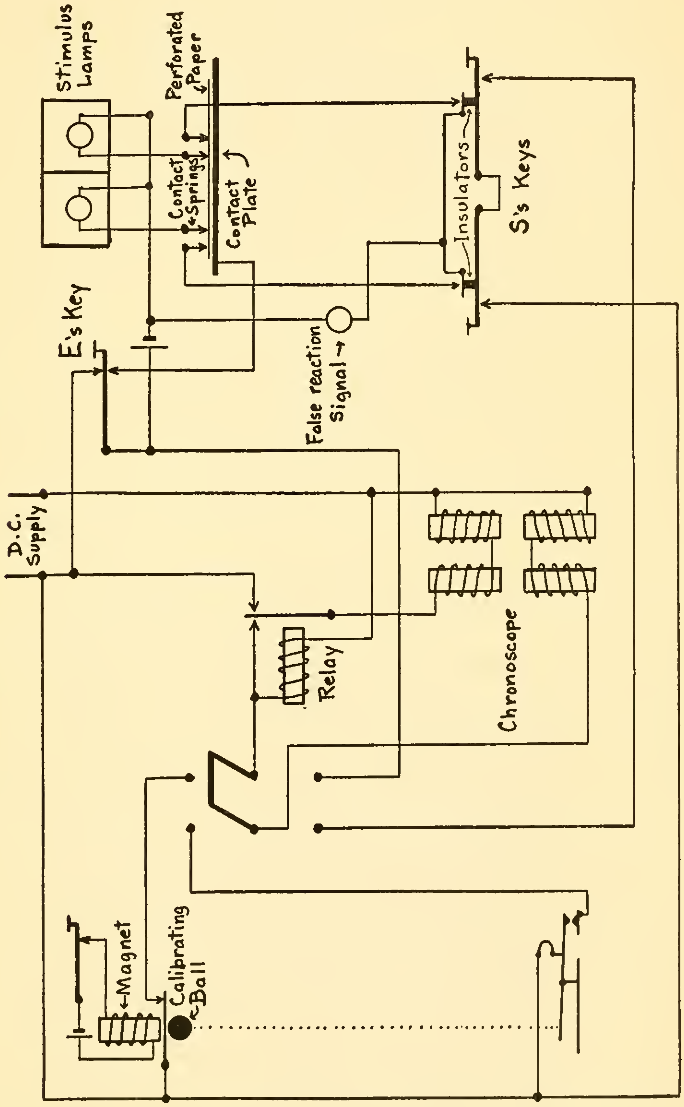
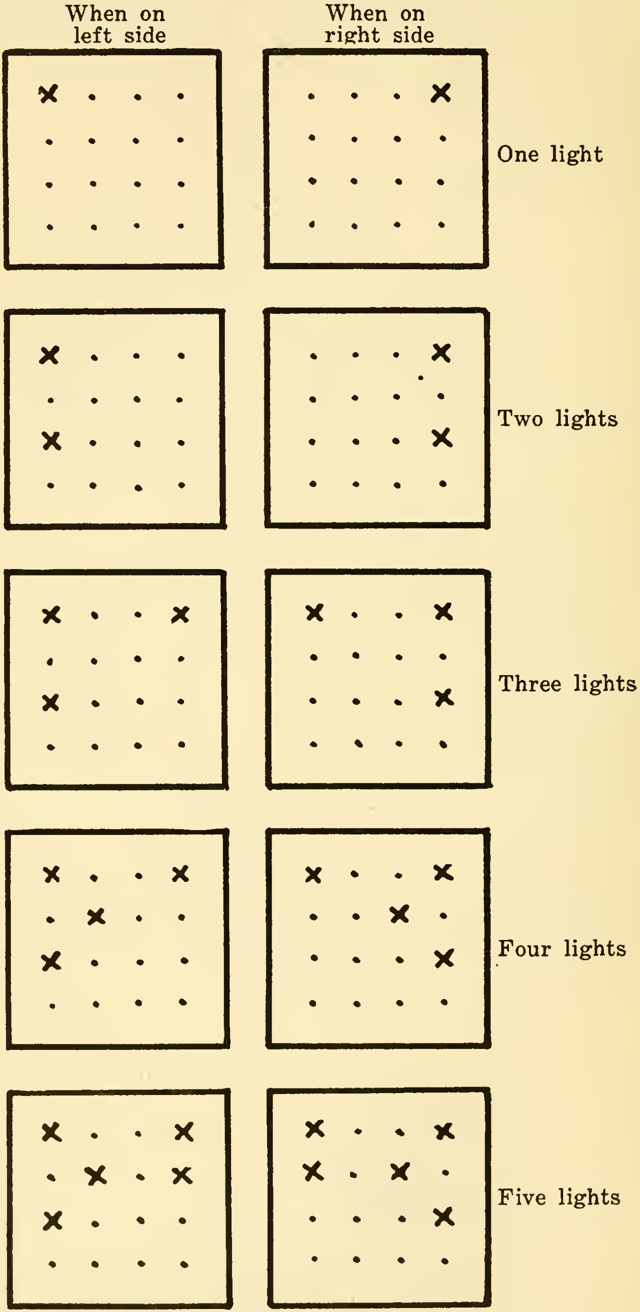


DIAGRAM I.

SCHEMATIC CIRCUIT DIAGRAM

DIAGRAM II
POSITIONS OF LIGHTS FOR VARIOUS COMBINATIONS



Note: Crosses indicate lamps which are lighted.

a. Simple Reaction

The simple reaction, referred to hereafter as "SR," was measured first, in order to obtain the subject's maximum reacting speed. This could not have been obtained so readily had a discriminative reaction been measured first, owing to the probable "hold-over" of the slightly hesitant discriminative attitude. The stimulus for "SR" was the simultaneous lighting of the upper left corner lamp on the left half of the stimulus board and the upper right corner lamp on the right half. Two lamps were used in order to avoid giving the subject any practice in reacting to a light on one side only of the board, a stimulus situation which was later employed in the easiest discriminative reaction.

One reaction key only was used in the simple reaction. The subject was asked which hand he preferred to use, and was required to use that hand throughout the series. He was instructed to depress the key when the experimenter said "Ready," to watch the stimulus board, and to raise his hand from the key as quickly as possible when the lights appeared. A preparatory or warning interval of approximately two seconds was used for all reactions. The subject was told not to depress his key again immediately after making a reaction, but to wait until the experimenter gave the next ready signal. Thus a series of short rests was interspersed between the reactions, tending to minimize fatigue. This procedure was followed in reactions of all types.

Since the subjects were inexperienced in reaction experiments, it was deemed inadvisable to confuse them by explaining the difference between the "sensory" and "motor" type reactions. It is likely that the instructions as given tended to produce a reaction approximating the sensory type, which was probably desirable in view of the fact that the later discriminative reactions were almost necessarily of this type.

The subject first made a few practice reactions in order to become familiar with the situation, after which he made a series of forty measured reactions, the average time of which, in milliseconds, was taken as his "score" on this test.

b. Easiest Discrimination

The second series consisted of forty reactions of the easiest type of discrimination, preceded by a few practice reactions.

The stimulus was the lighting of a single lamp on either the left or right side of the board. The subject was instructed to press down one key with each hand at the ready signal, to watch the stimulus board, and, when a lamp lighted, to raise as quickly as possible the hand on the side on which the light appeared. The key not involved in a reaction was kept depressed until called for by a subsequent stimulus. The subject was instructed to inform the experimenter whenever he became aware that he had made a false reaction, although the experimenter had already been apprised of the mistake through the medium of the false reaction signal. This procedure tended to keep the subject's attention at a high level and to prevent him from becoming careless. The stimulus light appeared in an irregular order on the left and right sides, but the total numbers of left and right appearances were equal.

This type of discrimination is referred to hereafter as "1-0," in accordance with a uniform scheme of designation in which each of the two figures separated by a hyphen indicates the number of lights appearing simultaneously on one of the halves of the board; thus "1-0" means one light on one half and no lights on the other half. The position of the light is indicated in Diagram I.

c. Harder Discriminations

The final series consisted of 160 reactions, 40 of each of the four grades of more difficult discrimination. The series was preceded as usual by a short practice series. The discrimination in each case was between two groups of lights, differing in number by one, which appeared simultaneously on the two halves of the board. The subject was instructed to press down both keys at the ready signal, to watch the stimulus board, and, when the lamps lighted, to raise as quickly as possible the hand on the side on which the *greater number* of lights appeared. He was requested to indicate false reactions.

The four grades of discrimination were: discriminating one light from two; two from three; three from four; and four from five; or, in accordance with the designating scheme previously referred to: "1-2"; "2-3"; "3-4"; and "4-5." The designation "1-2," for example, indicates one light on the left and two lights on the right, thus calling for a right-hand reaction, whereas "2-1" would indicate the same combination, but with the larger number on the left, calling for a left-hand reaction. However, in order to avoid complicating the tables and discussions, the designation "1-2" is used hereafter to mean both "1-2" and "2-1," and analogously for the other designations.

The positions of the lights for the various grades may be determined from Diagram II. A number of arrangements of lights were experimented with in preliminary trials, which resulted in the final selection of a series of combinations giving approximately equal increments of discrimination time from grade to grade.

The four grades were presented in an irregularly mixed order. If instead of this procedure, any one grade, such as "2-3," for example, had been given forty times in succession before going on to the next grade, it is quite possible that the subject would soon have learned that the three-light side could be distinguished from the two by some particular light which appeared in a certain position. He would then probably look for that light, and make his reaction to it alone rather than to the entire stimulus, which would undoubtedly make the discrimination considerably easier. If this should happen for each of the grades, they would tend to approximate a common level of difficulty. Such simplifications cannot well occur with the mixed presentation, however. The subject cannot learn to make his reaction to one light only of the three combination, for example, for this combination appears as many times in conjunction with four lights as with two lights, being reacted to in the latter case but not in the former.

The order of presentation of the four grades was not absolutely random, as care was taken to have each grade followed an equal number of times by each other grade, in order to equalize any effect which one reaction might have upon the succeeding reaction. Right and left hand reactions were equal in number.

Each subject thus made a total of 240 reactions, 40 of each type, and the entire experiment involved the measurement of over 27,000 reaction times.

V. THE CORRELATED MEASURES

The term "correlated measures" refers to all the tests which were correlated with reaction time. These comprised one standard test of general intelligence (Thorndike), three memory tests, and three learning tests. The memory and learning tests, or others very much like them, have been used in many investigations. They are based upon well-established principles, and are probably satisfactory measures of certain aspects of the capacities which they purport to test.

1. The Intelligence Test

The Thorndike Intelligence Examination for High School Graduates, which is generally considered one of the most comprehensive tests of "general intelligence" available, has been used for seven years as one of the tests for entrance at Columbia and other colleges. It requires three and one-half hours to administer, and does not place undue emphasis on speed. It correlates +.60 with Freshman year achievement as measured by grades, and has a reliability coefficient of .85, according to Wood (22).

2. The Memory Tests

a. LOGICAL MEMORY TEST. This is a test of ability to remember and reproduce ideas in orderly sequence. A pamphlet of about five pages of difficult prose, covering a topic judged to be unfamiliar, was given to each subject, who was allowed twenty minutes in which to study it. The pamphlets were then collected and a quiz of twelve questions given, which the subjects answered from memory. The answer to each question was later scored on a scale from 0 to 4 according to a prearranged key, so constructed as to make the scoring as objective as possible. Verbatim reproduction was not required, the score depending upon the essential ideas remembered.

b. AUDITORY PAIRED ASSOCIATES TEST. This is a test of rote memory for disconnected words. Twenty-five pairs of fairly difficult words were read to the subjects at intervals of three seconds. Slips of paper containing twenty-five numbered blanks were then passed out. The tester next read the first words of the pairs at intervals of about five seconds, after instructing the subjects to write down the second word of each pair as the first word was read. The presentation and test were then repeated, the same procedure being used. The score was the total number of correct reproductions on both trials.

c. VISUAL PAIRED ASSOCIATES TEST. This is a test of rote memory for disconnected words presented visually. The subjects were shown twenty-five pairs of words printed in large type on separate cards, each card being exposed for three seconds. A second set of cards, each containing the first word only of a pair, was then exposed, five seconds being allowed for each card. The subjects were instructed to write down on prepared blanks the second word of each pair as the first word was shown. A second presentation and trial were then given. The score was the total number of reproductions on both trials.

3. The Learning Tests

The first two learning tests, described below in (a) and (b), are intended to measure quickness in the acquisition of certain fairly simple associative connections. The learning test described in (c) is somewhat more difficult than the other two.

a. THE TURKISH-ENGLISH TEST. At the top of the test sheet was a key consisting of twenty Turkish words, printed in English letters, with their English equivalents. The test proper, occupying the remainder of the sheet, consisted of 100 Turkish words, each of the twenty words of the key being repeated five times in an irregular order. The subjects were instructed to write beside each word its English equivalent, and were allowed to refer to the key as often as necessary. They were instructed to take the words in order without skipping. Two trials of ten minutes each were given, the score being the total number of equivalents written in both trials.

b. THE DIGIT-SYMBOL SUBSTITUTION TEST. The blank for this test, which was devised by Whipple, is illustrated by Pyle (15). At the top of the test sheet were nine circles, each containing a digit and an arbitrary symbol, such as a cross, triangle, = sign, etc. Below were two columns of five-digit numbers, twenty in each column. Beside each number was a row of five squares in which the subjects were instructed to write the five symbols corresponding to the digits of the number. As before, the subjects were permitted to refer to the key as often as necessary. Two trials of four minutes each were given. The score was the total number of substitutions for digits made in both trials.

c. THE CODE TEST. This test was based on Test No. 6 at the "average adult" level in the Stanford Binet series. The code alphabet, which was exactly the same as the one used by Terman, was printed at the top of the sheet. Below was a paragraph of about 100 words, which the subject was instructed to write in code, referring to the code alphabet as often as necessary. The score was the number of letters coded in ten minutes.

VI. PRESENTATION AND DISCUSSION OF RESULTS

1. *The Averages*

Table I, which summarizes the data, gives the average times for the six types of reaction and the average scores for the correlated measures, with standard deviations, reliability coefficients, and numbers of cases. In addition are given the average values of three other measures, viz.: the total number of false reactions, "combined discriminations," and "average improvement ratio."

The "combined discriminations" measure was obtained for each subject by combining his times for the four most difficult

TABLE I

MEANS, STANDARD DEVIATIONS, RELIABILITY COEFFICIENTS, AND NUMBERS OF CASES

Test	Mean	Std. Dev.	Reliability Coeff.	No. of Cases
SR	199.1	25.5	.88	113
1-0	290.3	29.7	.91	113
1-2	475.5	61.8	.91	113
2-3	566.3	101.5	.95	113
3-4	656.0	150.2	.95	113
4-5	741.5	212.4	.95	113
F	13.1	8.98		113
Comb. Disc.	1291.3	232.0		113
Av. Imp. Ratio	1.087	.070		113
T	85.4	12.5	.85	109
LM	31.5	5.44	.60	88
PA	21.0	9.24	.85	94
PV	33.6	9.61	.94	89
TE	156.9	43.0	.91	91
DS	289.3	48.4	.95	92
C	193.8	39.9	.83	94

Means for the six reaction time tests are in milliseconds; for the other tests in score units.

KEY

SR	Simple reaction time	T	Thorndike Intell. Test
1-0	Discrim. 1 light from 0	LM	Logical memory
1-2	Discrim. 1 light from 2	PA	Paired Associates (auditory)
2-3	Discrim. 2 lights from 3	PV	Paired Associates (visual)
3-4	Discrim. 3 lights from 4	TE	Turkish-English
4-5	Discrim. 4 lights from 5	DS	Digit-symbol
		C	Code

Comb. Disc.	Combined Discriminations
F	Total number of false reactions
Av. Imp. Ratio	Average Improvement Ratio

discriminations (i.e., "1-2," "2-3," "3-4," and "4-5"), equalizing the weighting by allowing for the differences in the standard deviations. This was done according to the method described by Garrett (3, pp. 279-281). The score for the "1-2" test, which had the lowest standard deviation, was used unchanged, but the score on each of the three other tests was multiplied by the factor which would make its standard deviation equal to that of the "1-2" test. The four values thus obtained were added to give the "combined discriminations" score.

A subject's "average improvement ratio" is the average of his separate improvement ratios for the four most difficult discriminations, the improvement ratio for any one discrimination being the ratio of the average time of the first twenty reactions to the average of the second twenty reactions.

The average reaction times indicate a series of discriminations of progressively increasing difficulty. The unusually large difference in time between "1-0" and "1-2" is probably due to the fact that the methods of presentation were different, the former being given by itself and the latter mixed with others. The time increments between grades presented in a similar manner, however, are approximately equal.

2. *The Reliability Coefficients of the Tests*

The reaction time measurements were treated as tests and their statistical reliabilities determined by self-correlation. The first half of a test was correlated with the second, and the resulting coefficient corrected by the Spearman-Brown prophecy formula for a test of double length. The reliability of the Thorndike test was assumed to be the same as that found by Wood (22). This assumption could be made because the standard deviation and number of cases of the group studied by Wood were approximately the same as in the present group. See Kelley (8, p. 222). The reliabilities of the other correlated measures were obtained by the self-correlation method, using repeated trials, or alternate items (i.e., the "split half technique") where only one trial was given.

With the exception of the coefficients of .60 for the logical memory test and .83 for the code test, the reliabilities of all the tests equal or exceed that of the Thorndike test, which is .85. The reliability coefficients of the reaction time measures range from .88 to .95, and are, on the whole, higher than the reliabilities of the tests which are correlated with them.

3. *The False Reactions*

Wells (20), after studying the data obtained by Henmon and himself, concludes that false reactions tend to fall into two classes: abnormally fast or "quasi-premature" reactions, and unduly prolonged reactions. In the long run these types tend to offset each other, so that the average time of false reactions does not differ consistently from the average time of correct reactions. In the present study, however, the false reactions did not fall equally into the two classes; the large majority were faster than the correct reactions to the same stimuli.

The percentages of false reactions occurring in each type of discrimination were as follows:

1-0	2.7%
1-2	1.9%
2-3	4.9%
3-4	7.1%
4-5	14.8%

The "1-0" test was the first discrimination attempted, which probably accounts for the fact that more false reactions were made in it than in the next harder discrimination, "1-2." With this exception, the numbers of false reactions increase with the difficulty of discrimination.

Another interesting characteristic of the false reactions is that their average time for the different grades of discrimination tends to parallel the average time for the correct reactions. For example, it not only takes longer to react correctly to "4-5" than to "3-4," but it also takes longer to make a false reaction to "4-5" than to "3-4." This seems to indicate that the cause of a false reaction is not merely a "set" to react with a particular hand which is in such a state of readiness that it may be touched off by the stimulus for either hand. There seems to be an abbreviated or attempted discrimination of some sort, and this requires the more time the harder the combination to be reacted to.

False reactions have been omitted in computing average reaction times, but each subject's *total number* of false reactions was determined, and it is the distribution of these totals which is referred to in the later discussion as "F."

4. The Intercorrelations of the Reaction Time Tests

In Table II the reaction time tests have been arranged, both horizontally and vertically, in order of difficulty of discrimination, which makes it quite evident that there is a general tendency for the tests to correlate with each other the higher, the nearer alike they are in difficulty. The intercorrelations between the four most difficult grades of discrimination are high enough to suggest that these tests must be measuring nearly the same thing. This makes it possible to obtain a more reliable measure of discrimination by combining all four tests as previously described (page 22) to give a "combined discriminations" score, which is used hereafter in most of the discussion in place of the separate tests. This procedure reduces the complexity of the results without sacrificing any essential information.

TABLE II

INTERCORRELATIONS OF THE REACTION TIME TESTS

	SR	1-0	1-2	2-3	3-4	4-5	F
SR	.88						.29
1-0	.54	.91					.35
1-2	.32	.58	.91				
2-3	.30	.53	.91	.95			
3-4	.27	.42	.85	.92	.95		
4-5	.29	.41	.81	.89	.93	.95	
Comb. Disc.	.31	.49					.61

Key same as for Table I

Henmon and Wells (7) conclude, on the basis of their extensive joint researches on reaction time, that "Individual differences in simple and compound reactions persist after very long periods of practice, and rest on more fundamental differences than those of practice and direction of attention. There appears to be also a surprising lack of correlation between the times for simple and compound reactions." The statement in the last sentence seems to be based mainly upon data obtained by Henmon (6) from experiments in which both he and Wells served as subjects. Even after long practice, one of the experimenters remained faster in simple reactions while the other remained faster in discriminative reactions (discriminating red and yellow). This single instance, however, should not be considered as proving a negative correlation, or even a lack of correlation, since such cases would occur occasionally or even frequently with any correlation less than +1.00. In the present study the correlation (for 113 subjects) between the simple reaction and the easiest discrimination was +.54, and that between the simple reaction and "combined discriminations" was +.31 (Table II). These coefficients indicate a rather marked positive relationship.

5. *The Correlations of Zero Order between Speed of Reaction and the Other Tests*

Table III presents the complete series of product-moment correlation coefficients of zero order. The number of cases involved in any correlation may be determined from Table I; it is the smaller of the numbers of cases corresponding to the two correlates. The probable errors of all the coefficients being so nearly alike, inclusive values are given at the bottom of the table, in order to avoid the confusion resulting from the usual method of distributing the probable errors throughout the table.

Table III

CORRELATIONS OF ZERO ORDER BETWEEN REACTION SPEED AND THE OTHER TESTS

	Intel.	Memory			Learning		
	T	LM	PA	PV	TE	DS	C
SR	.04	.17	.20	.17	.26	.21	.16
1-0	.01	.14	.07	.03	.11	.21	.17
1-2	.03	—.03	.00	—.02	.25	.28	.10
2-3	.10	—.09	.03	—.05	.27	.25	.00
3-4	.17	—.04	.06	.01	.35	.29	.08
4-5	.17	—.01	.09	.03	.33	.25	.03
Comb. Disc.	.12	—.04	.06	.00	.29	.28	.05
Av. Imp. Ratio	—.01	—.11	—.04	.03	.02	—.10	—.07
F	—.13	—.04	—.01	—.01	.13	.16	—.16

Key same as for Table I
Probable errors for most correlations lie between .06 and .07

A positive correlation between reaction time and intelligence is apt to be interpreted uncritically to mean that rapid reaction tends to go with high intelligence. Strictly, however, it means just the reverse, for a high reaction *speed* is indicated by a low reaction *time,* and a given positive correlation with *reaction time* is equivalent to a negative correlation of the same magnitude with *reaction speed.* Instances of both usages exist in the literature. In order to avoid any possible misinterpretation, therefore, the term *reaction speed* is used henceforth instead of *reaction time,* and all the correlations reported are between *reaction speed* and the scores on the other tests.

Of the 49 correlations between reaction speed and measures of intelligence, memory, and learning reported in Table III, 42 are positive, and the remaining seven have very low negative values.

The correlation of the Thorndike test with simple reaction speed is +.04, and there is a general tendency for the Thorndike correlations to increase as the difficulty of the correlated discrimination tests increases, the maximum coefficient being +.17.

The correlations of the three memory tests with "SR" range from +.17 to +.20, but, unlike the Thorndike correlations, the memory correlations tend to decrease or become negative as the discriminations become harder. This tendency is particularly marked in the case of the logical memory test.

The correlations of the Turkish-English and Digit-Symbol learning tests with "SR" are +.26 and +.21 respectively, and their correlations with the discriminative reactions tend to increase with increasing difficulty of discrimination, reaching a maximum of +.35. The Code test, although grouped with the learning tests; bears a closer resemblance to the memory tests with respect to the behavior of its correlations.

The interpretation of coefficients of correlation is a matter on which there is not yet perfect agreement, and which may easily be overdone. The coefficient is in itself an interpretation of data, being the mathematical expression of a relationship which formerly had to be described clumsily and inaccurately in words. To "interpret" a coefficient, therefore, by saying that it indicates a "high," "moderate," or "low" degree of relationship is to return to the former unsatisfactory method of description. However, correlation coefficients may legitimately be characterized as useful or not useful for purposes of prediction, or as indicating the presence or absence of common factors.

The correlations in Table III are all too low to have any value in prediction. Garrett (3, pp. 289-290) says: "For r's of .30 and less, the coefficient of alienation is so large that the predictions based on them are but little better than a guess." Furthermore, correlations of this size do not, ordinarily, imply the presence of a very high percentage of common factors. See Garrett (3, p. 294). It is hardly safe to regard the problem as settled by these two considerations, however, for a series of consistent results is apt to have a significance not possessed by a single item, especially when the results are based upon original data having a high degree of reliability. For example, the correlation of +.26 between "SR" and the "TE" learning test might, taken by itself, warrant the assumption that the two tests do not have many factors in common, but when five correlations between this test and reaction speed are all positive and between .25 and .35, the consistency in magnitude and sign suggests that *some* common factors are definitely present. Altogether, there are six times as many positive as negative correlations between reaction speed and the other tests. This very unequal distribution would be most unlikely to occur under the influence of chance alone.

The Thorndike correlations indicate that intelligence may have factors in common with discriminative reaction speed, but is probably not similarly related to simple reaction speed.

The memory tests (and the Code learning test) are about as closely related to simple reaction speed as the Thorndike test is to discriminative reaction speed. It is not advisable to say that simple reaction speed "is a factor in memory," for to consider the simple reaction as a unitary factor is unduly to simplify a process which is probably quite complex, in spite of its name. It is safer merely to say that memory and the simple reaction have factors in common. The memory (and code) tests are, however, only slightly, or negatively related to discriminative reaction speed.

The "TE" and "DS" learning tests are more closely related to both kinds of reaction speed than are any of the other tests. The reason for this may be that the learning tests depend more upon speed than do the Thorndike and memory tests, and the reaction time tests are principally measures of speed. The relationship of the learning tests to the discriminative reactions is closer than to the simple reactions.

6. *The Reliability of the Correlations*

The probable errors of all the correlations lie between .06 and .07. This means that all correlations over about .25 can be considered statistically reliable, if reliability be judged by the usual criterion of four times the probable error. The lower correlations, however, were computed from original data just as reliable as those involved in the higher correlations; their unreliability is an inherent consequence of their small size. For example, assuming the correlation of .01 between "1-0" and Thorndike to be the true value, to make this correlation conventionally reliable, that is, to reduce its probable error to one quarter of the correlation or .0025, would necessitate testing 73,000 cases, involving a fair lifetime of work. It should not be assumed, however, that because a very low correlation cannot be made statistically reliable it is therefore unimportant or without significance. It indicates a probable absence of relationship, which is just as important from the standpoint of theoretical psychology as the presence of relationship would be.

A relatively low probable error renders it *probable* that the coefficient applies also to the "total population" of which the test group forms a random sample. However, any theoretical certainty deriving from the low probable error is usually counteracted in practice by the much greater uncertainty as to just what that "total population" is. Almost invariably it will prove to have been selected (but *not* randomly) from some still larger population, and so on indefinitely. Generalization can never proceed with safety very far from the test group. All correlations, whether large or small, if based upon reliable data, give valuable information concerning the relations obtaining within the group tested.

7. *The Corrections for Attenuation*

In conformity with current practice, the principal correlations have been corrected for attenuation (Table IV). This procedure is probably not, in general, of very great value. If the correlates are of low reliability, the corrected coefficients cannot be considered of very great reliability either. On the other hand, if the correlates are very reliable the attenuation correction will necessarily be very small. In any event, the corrected coefficients are merely estimates of what

TABLE IV

EFFECT OF CORRECTING FOR ATTENUATION

		Intel.	Memory			Learning		
		T	LM	PA	PV	TE	DS	C
SR	Original	.04	.17	.20	.17	.26	.21	.16
	Corrected	.05	.23	.23	.19	.29	.23	.19
1-0	Original	.01	.14	.07	.03	.11	.21	.17
	Corrected	.01	.19	.08	.03	.12	.23	.20
Comb. Disc.	Original	.12	—.04	.06	.00	.29	.28	.05
	Corrected	.13	—.05	.07	.00	.31	.29	.06

Key same as for Table I

might have been obtained had there been no disturbing factors or errors of measurement, a condition which never obtains in practice. It is dangerous to let a simple calculation take the place of careful control of experimental conditions.

In the present instance, the high reliability of the tests results in low corrections, varying from zero to .06. The original coefficients were used in computing the partial correlations.

8. *The Partial Correlations*

An individual's time for a discriminative reaction depends not only upon his speed in discrimination or perception, but is probably influenced also by his simple reaction speed, assuming the latter to be, in effect, a measure of the maximum speed with which the neuro-muscular apparatus can react. In the early days of reaction time experiments, before the "fallacy of subtraction" was pointed out, "discrimination time" was determined by subtracting the time for a simple reaction from the time for a discriminative reaction. See Woodworth and Poffenberger (24), pp. 179-180. A more acceptable mode of attack upon the problem is now available in the partial correlation technique. The correlations between the various tests and discriminative reaction speed, with simple reaction speed partialled out, should indicate more nearly the true relation existing between the tests and pure discrimination speed.

Furthermore, there is a substantial positive correlation between number of false reactions and reaction speed in all grades, which means that the persons making the most errors tend to make the fastest reactions. This suggests that there are at least two factors tending to make for a fast reaction, viz.: speed in discrimination itself, and carelessness, or the attempt to gain speed regardless of accuracy. Considering the total number of false reactions made as a measure of carelessness, the effect of this factor can be minimized by partialling out the "total number of false reactions" score (i.e., "F"). Thus a uniform attitude toward the test, which is so difficult to secure experimentally, is, in effect, approximated statistically. The resulting coefficients should express more nearly the true relationship of the tests with discrimination speed.

Finally, partialling out both "SR" and "F" should give the best measure of the relationship just mentioned which can be obtained from the data.

Table V shows that the effect on the Thorndike correlations of partialling out "SR" is negligible, but partialling out "F," and "SR" and "F" together, practically doubles the coefficients, giving a maximum of +.25. This indicates that carelessness probably tended to obscure the true relationship.

In the case of the memory correlations, partialling out "SR," and both "F" and "SR," brings about a considerable reduction, whereas partialling out "F" produces practically no change in the coefficients. Here, simple reaction speed seems to have been an obscuring factor, making the correlations higher than was warranted by the true relationship with discrimination speed.

The "TE" and "DS" learning tests were affected by the partialling process in the same manner as the memory tests, but the Code test did not follow any of the types consistently. This test seems to be in a class by itself, resembling intelligence, memory, or learning tests according to the manner of comparison.

Taken as a whole, the results of the partialling do not materially alter the conclusions already drawn. They suggest, however, that the *relative* importance of pure discrimination speed, as compared with simple reaction speed, is greater in the case of intelligence and learning, and less in the case of memory, than is indicated by the zero order correlations.

TABLE V

PARTIAL CORRELATION COEFFICIENTS

Variables Correlated	Zero Order	With SR Eliminated	With F Eliminated	With SR and F Eliminated
SR* and T*	.04		.08	
SR and LM	.17		.19	
SR and PA	.20		.21	
SR and PV	.17		.18	
SR and TE	.26		.23	
SR and DS	.21		.17	
SR and C	.16		.22	
1-0 and T	.01	—.01	.06	.02
1-0 and LM	.14	.06	.16	.08
1-0 and PA	.07	—.05	.08	—.03
1-0 and PV	.03	—.08	.04	—.06
1-0 and TE	.11	—.04	.07	—.05
1-0 and DS	.21	.12	.17	.09
1-0 and C	.17	.10	.24	.16
Comb. Disc. and T	.12	.11	.25	.25
Comb. Disc. and LM	—.04	—.10	—.02	—.06
Comb. Disc. and PA	.06	.00	.08	.05
Comb. Disc. and PV	.00	—.06	.01	—.02
Comb. Disc. and TE	.29	.23	.27	.24
Comb. Disc. and DS	.28	.23	.23	.21
Comb. Disc. and C	.05	.00	.19	.16

*Key to symbols same as for Table I

9. *The Correlations with Improvement Ratio*

As previously stated, the first twenty and last twenty reaction times of each subject in each test were averaged separately, in order to find the self-correlations. These values afforded a convenient means of investigating a certain minor relationship. The average of the first half divided by the average of the second half was called the improvement ratio; a value greater than 1.00 thus indicated that the reactions became faster with practice. This ratio was really a measure of the subject's "learning ability" in reacting, and it was therefore possible to determine whether learning ability of this rather simple type is correlated with the more complex types of learning ability as measured by the learning tests proper. Correlations were computed of "average improvement ratio" (as defined on page 22) with the learning tests, and with the intelligence and memory tests also. The results, given in Table III, show a preponderance of small negative values, but the correlations are not sufficiently consistent to warrant any definite conclusions.

10. The Regression Equation Expressing Intelligence in Terms of Reaction Speed, Memory, and Learning

Although it was not the purpose of this study to investigate the nature of intelligence, enough data were at hand to make it possible to form a regression equation showing the relative "weights" with which simple and discriminative reaction speed, memory, and learning enter into intelligence as measured by the Thorndike test. Simple reaction speed was measured by the "SR" test; discriminative reaction speed by "Comb. Disc." (combined discriminations); memory by the auditory paired associates test; and learning by the Turkish-English test. The latter two tests were selected for this purpose because they correlated fairly highly with the Thorndike test and had high reliabilities.

The regression coefficients of the equation were determined by the method described by Tolley and Ezekiel (19), which is based upon the method of least squares and does not require the computation of intermediate partial correlation coefficients. All the standard deviations were taken as equal; consequently the regression coefficients indicate the weights directly. See Garrett (3), page 256. The equation is:

$$\begin{aligned}\text{(Intelligence)} = &-.09\ \text{(SR)} + .05\ \text{(Comb. Disc.)}\\ &+ .18\ \text{(Memory)} + .30\ \text{(Learning)}\end{aligned}$$

If an equation of this type be multiplied by a properly chosen constant, as suggested by Kelley (9), page 14, the resulting coefficients will indicate more clearly the relative magnitudes of the weights. In this case, multiplying by 20 (which makes the smallest coefficient equal to 1.00) gives:

$$\begin{aligned}\text{(Intelligence)} = &-1.8\ \text{(SR)} + 1.00\ \text{(Comb. Disc.)}\\ &+ 3.6\ \text{(Memory)} + 6.00\ \text{(Learning)}\end{aligned}$$

This equation indicates that in this particular group of four factors, memory and learning are from two to six times as important, with respect to intelligence, as simple and discriminative reaction speed.

The multiple correlation of intelligence with the four factors combined is .40, which is about twice as large as the correlation which would be obtained were the variables uncorrelated. See Garrett (3), pages 238-239. This correlation indicates that intelligence cannot be satisfactorily predicted from a regression equation involving these four factors only, since the "error of estimate" in such a prediction would be at least nine-tenths of the standard deviation of the distribution.

VII. GENERAL CONCLUSIONS

In general, the results show that intelligence, memory, and learning all have factors in common with reaction speed. Intelligence and learning are more closely related to the discriminative reaction; memory to the simple reaction. Correlation coefficients, however, while they may indicate the presence of common factors, can give no direct information concerning their nature, and any conclusions on this point must necessarily be speculative.

The reaction time tests are primarily speed tests, and it therefore seems probable that speed is one of the common factors involved, perhaps the principal one. The speed of a simple reaction undoubtedly depends largely upon the speed of conduction of nervous impulses, both in sensory and motor nerves and in such nerve centers, connecting neurones, synapses, etc., as are involved in the reaction. Speed in a discriminative reaction can probably be reduced also to speed of conduction, but in this case there is greater "elaboration" (perhaps in association centers) before the final discharge of the nervous impulse. This elaboration probably involves a greater number of nerve centers, synapses, etc., than does the simple reaction, and more time is thus required for conduction. This results in a longer reaction time.

For speed of conduction to be the sought-for common factor, it must also be a factor in intelligence, memory, and learning. That speed is commonly considered to be one of the "aspects" of intelligence is evidenced by the inclusion of one or more speed test sections in the average intelligence test, such as the Army Alpha, for example.

Clark (2) found a correlation of +.50 between speed and total score on intelligence tests, and Peak and Boring (12) obtained correlations of +.90 and +1.00 between score and speed on the Army Alpha and Otis tests. In studies like these on the relation of speed to intelligence, speed is usually measured with material quite similar to that used in the intelligence or level tests. Thus little or no light is thrown on the question of the part which speed of conduction of nervous impulses may play in determining not only the "speed aspect" of intelligence, but the level or quality of intelligence.

Thorndike (18, p. 415) in a recent discussion of the nature of intelligence, suggests that quality or level of intelligence may ultimately be based upon quantity. He says: "The person whose intellect is greater or higher or better than that of another person differs from him in the last analysis in having, not a new sort of physiological process, but simply a larger number of connections of the ordinary sort." It is possible that the *quality* of intelligence may depend not only upon the *number* of connections, but also upon the *speed* with which these connections are formed. Nerve centers (e.g., association centers) cannot remain excited indefinitely at maximum intensity; consequently in the case of a person who forms connections slowly it is possible that the excitation of the first association centers to be affected will have diminished or disappeared before the later centers come into play. Thus only a limited number of centers are cooperating at any one time. The person who forms connections quickly, however, is apt to have more association centers interacting at once, since the later centers are aroused before the earlier have had a chance to lose their effectiveness. But the most intelligent response is, in general, the one in the determination of which the greatest number of factors have been taken into consideration. In neural terms this may well mean the response in the determination of which the greatest number of association centers have cooperated, and the number of simultaneously active centers may in turn depend to some extent upon the speed with which nervous impulses are conducted from center to center and through synapses within the centers. Conduction speed may play a similar role in learning of the higher types.

The fact that intelligence and learning correlate less with the simple than with the discriminative reactions is consistent with the hypothesis just presented, for the discriminative reactions probably involve more nerve centers of the association type than does the simple reaction. In the case of memory, however, the correlation with simple reaction is greater than with the discriminative reactions. This may imply that the centers involved in memory are different from those which are most important in intelligent responses and in learning of the higher types, and more like those involved in the simple reaction.

VIII. SUMMARY

A number of Columbia College students were given tests of intelligence, memory, and learning, and were also measured for simple and discriminative reaction time; the latter for five degrees of difficulty of discrimination. All the measurements possess a satisfactory degree of statistical reliability.

Correlations were computed between the reaction time measurements and the other tests, an attempt being made to isolate true discrimination speed by partialling out simple reaction speed and tendency to carelessness, the latter being indicated by the number of false reactions made.

The principal results and conclusions may be briefly summarized as follows:

a. Discriminative reaction speed is positively correlated with simple reaction speed, the coefficients ranging from +.27 to +.54; the harder the discrimination, the lower the correlation.

b. The correlations of the intelligence, memory, and learning tests with simple reaction speed differ from their correlations with discriminative reaction speed, and the latter vary with the difficulty of discrimination. The correlations are all too low for purposes of prediction, but are sufficiently consistent in magnitude and sign to suggest relationships which are probably genuine.

c. The correlation of *intelligence* with simple reaction speed is positive but negligibly small; the correlation of intelligence with speed in the harder discriminations becomes +.25 when the obscuring factors are partialled out.

d. The correlation of *memory* with simple reaction speed is about +.20, but decreases as the difficulty of discrimination increases, becoming slightly negative with the harder discriminations.

e. The correlation of *learning* ("TE" and "DS" tests) with simple reaction speed is about +.20; with discriminative reaction speed the correlations range from +.11 to +.35.

f. The correlations of *learning or improvement in the reaction time tests* with learning of the higher types as measured by the learning tests proper, and with intelligence and memory, are mostly low and negative, and are not consistent enough to be significant.

g. The correlations between simple reaction speed and memory agree fairly well with the value of +.12 found by Cattell and Wissler, and the corresponding correlation with intelligence is not far from the value of —.02 which the same investigators report for the correlation between reaction time and class grades.

h. The correlation of +.90 between reaction time and intelligence reported by Peak and Boring is not confirmed by the results of this study.

i. The hypothesis is advanced that speed of conduction in nerves and synapses is one of the most important common factors responsible for the correlations. It is further argued that this speed may, in part, determine the level or quality of intelligence and degree of learning ability possessed by a given individual.

j. The regression equation expressing intelligence in terms of simple and discriminative reaction speed, memory, and learning, shows that as factors in intelligence, memory and learning are from two to six times as important as reaction speed.

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